METHODOLOGY TO EVALUATE THE SERVICE LIFE OF CONCRETE

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DURABILITY

(Def. EN 13369) Ability of a precast concrete product to satisfy, with anticipated maintenance, the design performance requirements during its design working life under the influence of the expected environmental actions

Figure.- Pantheon, Rome (14 A.D.)

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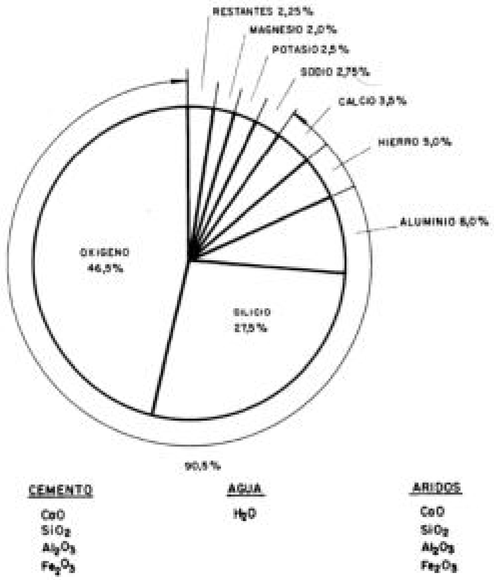
CONCRETE



- **Universal and local material → There are aggregates and raw materials everywhere to make cement and therefore concrete**

- **Use concrete $\geq 2 \cdot \Sigma$ other materials altogether**

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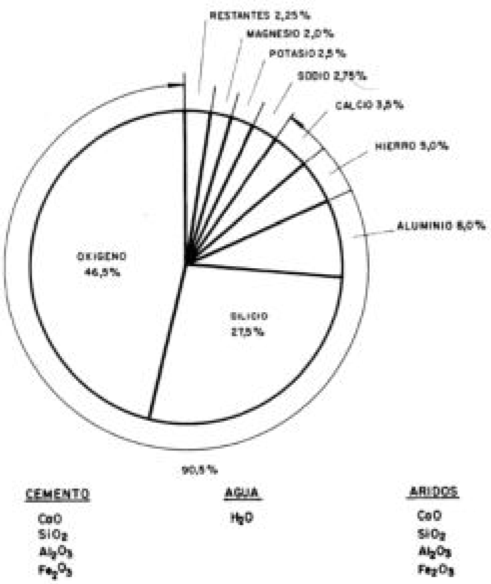
(SUSTAINABLE) CONCRETE

- **Massive material → good overall performance in terms of:**
  - **mechanical capacity**
  - **DURABILITY**
  - **thermal inertia**
  - **fire resistance**
  - **acoustic airborne noise**
  - **recyclable…**

- **Moldable (design) → Optimization**

- **Able to incorporate new raw materials to REDUCE THE ENVIRONMENTAL IMPACTS**



HOW TO MEET THE SERVICE LIFE?

Aspects to fulfil the **DURABILITY** of elements

1) Identification of the mechanisms of damage, depending on the type of exposure
2) Concrete mix design:
   - Selection of materials
   - W/C ratio
   - cement content
   - resistance
   - concrete cover

HOW TO MEET THE SERVICE LIFE?

Aspects to fulfil/improve the DURABILITY of the structure

- **Selection of suitable structural forms (structural design)**

HOW TO MEET THE SERVICE LIFE?

Specific measures against aggressiveness:

- Additional measures in the case of prestressed reinforcement
- Use of surface protection systems
- Use of corrosion inhibitor products
- Use of reinforcements with improved performance against corrosion

PRECAST (CONCRETE) PRODUCT

(Def. EN 13369) Product which is made of (*reinforced/prestressed*) concrete

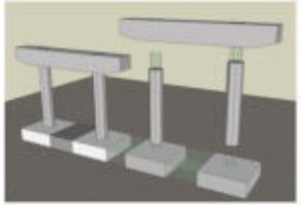
- Manufactured in accordance with a specific product standard

- In a place different from the final destination of use,

- Protected from adverse weather conditions during production

- Result of an industrial process under a factory production control system

- Have the possibility of sorting before delivery





DURABILITY APPROACH FOR PRECAST CONCRETE

How do the different standards tackle the durability?

- **Most of them, based on EN 1992-1-1 and EN 206, set prescriptions in W/C ratio, minimum cement content, minimum resistance and concrete cover, depending on the exposure classes.**

- **All the aspects mentioned for the precast concrete mean that we can have better performance than the standard ones.**

How can we appreciate that improvement?

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DURABILITY APPROACH

- **Durability requirements under Spanish technical regulation:**

0. **Fulfil strictly the durability parameters of the product standards (i.e. hEN´s → EN 206)**

1. **UNE 127050 → EN 12390-8 Testing hardened concrete - Part 8: Depth of penetration of water under pressure**

2. **Annex 12 of Spanish Structural Code**

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Methodology to evaluate the service life of concrete (1)

Bases on Spanish standard UNE 127 050"Industrialized Systems for Buildings Constructed from Prefabricated Concrete Elements"

- **Based on a feature of the finished concrete**
- **Establishes a relationship between:**

✓ **the service life of a concrete element and**

✓ **the result of the water penetration test under pressure (EN 12390-8)**

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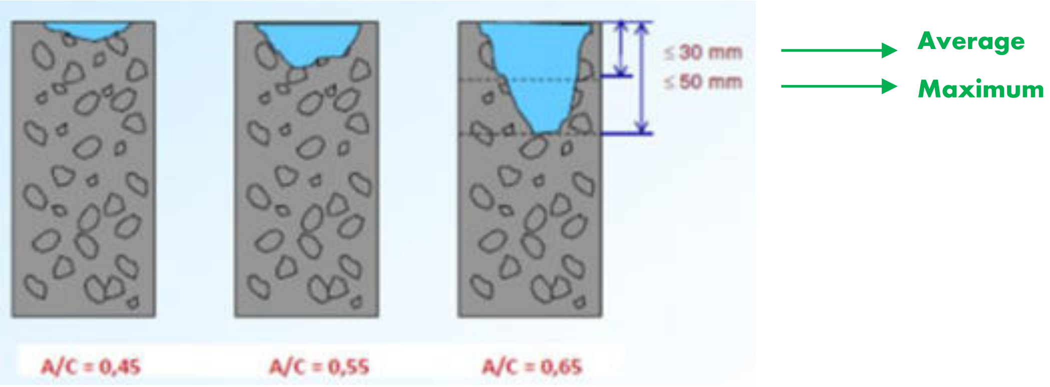
Methodology to evaluate the service life of concrete (1)

- **The specifications limits for depth penetration in the test are:**

Exposure class	Máximum	Average
XS1, XS2, XD1, XD2, XD3, XF1, XF2, XF3, XF4, XM, XA1 (always)	50 mm	30 mm
XA2 (reinforced and non-reinforced elements)		
XS3, XA3 (always)	30 mm	20 mm
XA2 (prestressed elements)		



Methodology to evaluate the service life of concrete (1)

Estimation of service life based on water penetration test under pressure (UNE 127 050)

- **If the concrete complies with the values that for each exposure class include the durability specifications in terms of minimum amount of cement, maximum water/cement ratio and minimum resistance,**

- **and if in the under pressure penetration test according to EN 12390-8, the results obtained are better than the minimums**

an improved service life can be attributed to the concrete design

according to the next two tables (the minimum value of both)

Methodology to evaluate the service life of concrete (1)

Estimation of service life based on water penetration test under pressure (UNE 127 050)

Máximum penetration (mm)	Nominal service life (years)
50	50
49	52
48	54
47	56
46	59
45	62
44	64
43	68
42	71
41	74
40	78
39	82
38	86
37	91
36	96
35	102
34	108
33	115
32	122
31	130
30	139
29	148
28	159

Average penetration (mm)	Nominal service life (years)
30	50
29	53
28	57
27	62
26	66
25	72
24	78
23	85
22	93
21	102
20	112
19	125
18	139
17	156

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Methodology to evaluate the service life of concrete (1)

Estimation of service life based on water penetration test under pressure (UNE 127 050)

Máximum penetration (mm)	Nominal service life (years)
50	50
49	52
48	54
47	56
46	59
45	62
44	64
43	68
42	71
41	74
40	78
39	82
38	86
37	91
36	96
35	102
34	108
33	115
32	122
31	130
30	139
29	148
28	159

Average penetration (mm)	Nominal service life (years)
30	50
29	53
28	57
27	62
26	66
25	72
24	78
23	85
22	93
21	102
20	112
19	125
18	139
17	156

Check the values of both tables and take the lowest one

Methodology to evaluate the service life of concrete (2)

- **Other alternative is the Annex 12 of Spanish Structural Code**

- **It provides the basis to calculate the time in which:**
  - ***corrosion by carbonation*** **(exposure XC) or**
  - ***corrosion by chlorides ions*** **(exposure XS and XD)**

damages the reinforced/prestressed concrete, to estimate its residual service life

Methodology to evaluate the service life of concrete (2)

Carbonation: If CO_2 penetrates the concrete, it reacts with the portlandite and forms calcium carbonate which, although it makes the concrete more compact, causes a reduction in pH and the possible depassivation of the reinforcement.

$$Ca(OH)_2 + CO_2 \rightarrow CO_3Ca + H_2O$$

Chlorides: If they reach the reinforcement, they depassivate it and cause corrosion, even at high pH values.

Methodology to evaluate the service life of concrete (2)

Annex 12 of Spanish Structural Code

Concrete deterioration is a two-stage process: initiation and propagation

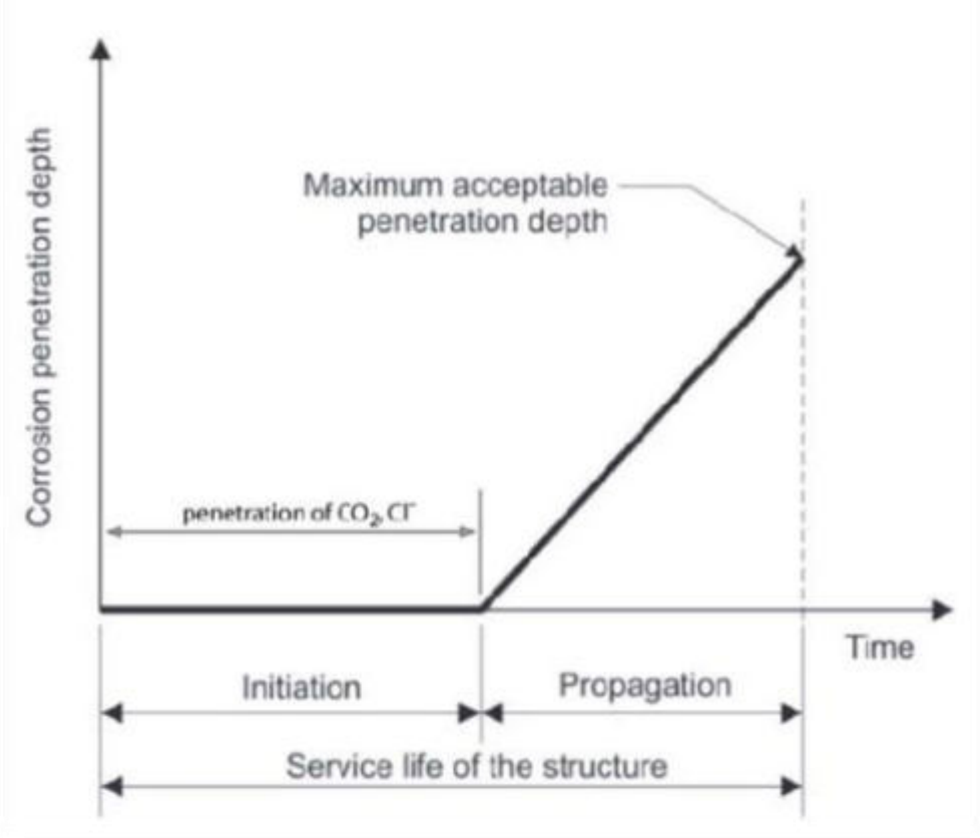
And the service life is the sum of both:

$$t_{est} = t_{inic} + t_{prop}$$

Methodology to evaluate the service life of concrete (2)

Initiation: Till the damage begins

Propagation: Till the damage in reinforcement is considered unacceptable



Methodology to evaluate the service life of concrete (2)

Models for the period of initiation: Carbonation (1)

For elements located in XC exposure classes, corrosion induced by carbonation, the initiation period is:

$$t_{inic} = (c \,/\, k_{ap,carb})^2$$

where

c minimum concrete cover (mm)

$k_{ap,carb}$ apparent carbonation coefficient (mm/year$^{1/2}$)

Methodology to evaluate the service life of concrete (2)

Models for the period of initiation: Carbonation (1)

The value of $k_{ap,carb}$ can be determined experimentally (UNE 83993-1)

In absence of experimental data, it can be estimate from the expression:

$$k_{ap,carb} = c_{env} \cdot c_{air} \cdot a \cdot (f_{ck} + 8)^{b}$$

Methodology to evaluate the service life of concrete (2)

Models for the period of initiation: Carbonation (1)

c_{env} the environment coefficient

Environment	c_{env}
Protected from rain	1
Exposed to rain	0.5
Buried elements, above the phreatic level	0.3
Buried elements, below the phreatic level	0.2

Methodology to evaluate the service life of concrete (2)

Models for the period of initiation: Carbonation (1)

c_{air} the aeration coefficient

Occluded air	c_{air}
< 4.5 %	1
≥ 4.5 %	0.7

Methodology to evaluate the service life of concrete (2)

Models for the period of initiation: Carbonation (1)

Parameters “a” and “b” to estimate the apparent carbonation coefficient

Binder (cement)	a	b
Portland cement	1800	-1.7
Portland cement + 28 % fly ash	360	-1.2
Portland cement + 9 % silica fume	400	-1.2

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Methodology to evaluate the service life of concrete (2)

"k" values within

EN 16 757 *

* **Sustainability of construction works - Environmental product declarations - Product Category Rules for concrete and concrete elements**

Table G.1 — k-factors [mm/year^{0,5}] for calculation of depth of carbonation for different concrete strength classes (cylinder) and exposure conditions and also degree of carbonation for different exposure conditions (Derived from [39])

Concrete strength class	< 16 MPa	16 to 20 MPa	25 to 35 MPa	> 35 MPa	Degree of carbonation (D_c)
Parameters	Value of k-factor, in mm/year^{0,5}				Percentage
Civil engineering structures					
Exposed to rain		2,7	1,6	1,1	85
Sheltered from rain		6,6	4,4	2,7	75
In ground [a]		1,1	0,8	0,5	85
Buildings					
Outdoor					
Exposed to rain	5,5	2,7	1,6	1,1	85
Sheltered from rain	11	6,6	4,4	2,7	75
Indoor in dry climate [c]					
With cover [b]	11,6	6,9	4,6	2,7	40
Without	16,5	9,9	6,6	3,8	40
In ground [a]		1,1	0,8	0,5	85

[a] Under groundwater level k = 0,2.
[b] Paint or wall paper. (Under tiles, parquet and laminate k is considered to be 0.)
[c] Indoor in dry climate means that the RH is normally between 45 % and 65 %.

Methodology to evaluate the service life of concrete (2)

Models for the period of initiation: Chlorides (2)

For elements located in exposure classes

XS, corrosion induced by chlorides from sea water, or

XD, corrosion induced by chlorides other than from sea water,

To determinate the advance of chlorides ions inside the concrete as function of time, we can use the following expression, based on the 2ª Fick´s diffusion law:

$$C_{th} = C_b + (C_S - C_b) \cdot \left[1 - erf\left(\frac{c}{2\sqrt{D_{app,C,}(t) \cdot t}}\right)\right]$$

Methodology to evaluate the service life of concrete (2)

Models for the period of initiation: Chlorides (2)

C_{th} limit content of chlorides ions in concrete that causes the beginning of corrosion in reinforcement

We have to probe t values and check that the limits are not exceded because the presence of error function

$$C_{th}=C_b+(C_S-C_b)\cdot\left[1-erf\left(\frac{c}{2\sqrt{D_{app,C,}(t)\cdot t}}\right)\right]$$

Methodology to evaluate the service life of concrete (2)

Models for the period of initiation: Chlorides (2)

With the value of the required service life, we get C_{th} value that mustn´t exceed the established in the following table according to the exposition classes.

Exposure class	C_{th}
XS1	0.60
XS2	0.80
XS3	0.60
XD1	0.60
XD2	0.60
XD3	0.40

Methodology to evaluate the service life of concrete (2)

Models for the period of initiation: Chlorides (2)

Other parameters involved are:

***C_b* chlorides content from the materials used in the manufacturing of concrete, incorporated from the mix, as % of cement weight**

***C_s* chlorides content in the concrete surface, incorporated from external sources, as % of cement weight**

Estimation of C_s chloride content in the concrete surface		
Exposure class	Distance L to the seaside m	C_s as % of concrete weight
XS1	Spray area, close to splashes	0.25
	Others L ≤ 5000 m	0.15
XS2	-	0.40
XS3	-	0.50
XD1, XD2, XD3	-	0.40

Methodology to evaluate the service life of concrete (2)

Models for the period of initiation: Chlorides (2)

erf **error function**

C **concrete cover (mm)**

t **time until corrosion starts (years)**

$D_{app,c}(t)$ **is the chlorides diffusion coefficient (mm²/year) that can be obtained experimentally for existing structures and for elements in the design phase through the expression**

$$D_{app,c}(t) = k_e \cdot D_{app,c}(t_0) \cdot (t_0/t)^n$$

Methodology to evaluate the service life of concrete (2)

Models for the period of initiation: Chlorides (2)

$D_{app,c}(t_0)$ depends of the w/c ratio and the type of cement

$D_{app,c}(t_0)$ diffusion chlorides coefficient got with NT BUILD 492 standard (x 10^{-12} m^2/s)				
Type of binder	w / c ratio			
	0.35	0.40	0.45	0.50
CEM I	-	8.9	10.0	15.8
CEM II/BV, CEM I with additions >22% fly ashes	-	5.6	6.9	9.0
CEM I with additions silica fume >5%	4.4	4.8	-	-
CEM III/B	-	1.4	1.9	2.8

Methodology to evaluate the service life of concrete (2)

Models for the period of initiation: Chlorides (2)

n **aging coefficient that can be derived from the next table**

w / c ratio	Type of cement	n aging coefficient
0.4 – 0.5	CEM I	0.3
Others		0.5

k_e coefficient that depends on the average environmental temperature, T_{real} (ºC), according to the following expression:

$$k_e = e^{4800 \cdot (1/293 - 1/(273 + T_{real}))}$$

Methodology to evaluate the service life of concrete (2)

Models for the period of initiation: Chlorides (2)

The error function can be conservatively simplified by using the next parabola function:

$$C_{th} = C_b + (C_s - C_b).\left[1 - \frac{x}{\sqrt{12 \cdot D_{app,c}(t).t}}\right]^2$$

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Methodology to evaluate the service life of concrete (2)

Model for the period of propagation

The model for the period of propagation is the same for Carbonation and Chlorides ions penetration and it has two parts:

- **Corrosion time to crack the cover**
- **Corrosion time for an unacceptable loss of diameter in the reinforcement**

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Methodology to evaluate the service life of concrete (2)

Model for the period of propagation

Corrosion time to crack the cover

$$t_{fis,corr} = 80 \cdot c \,/\, (Ø \cdot \vartheta_{corr})$$

being:

C concrete cover (mm)

Ø reinforced diameter (mm)

ϑ_{corr} corrosion speed

Methodology to evaluate the service life of concrete (2)

Model for the period of propagation

ϑ_{corr} corrosion speed (μm/year), according to the table below:

Exposure class	ϑ_{corr} μm/year
XC1	1
XC2	4
XC3	2
XC4	5
XS1	20
XS2	4
XS3	50
XD1	35
XD2	20
XD3	35

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Methodology to evaluate the service life of concrete (2)

Model for the period of propagation

Corrosion time for an unacceptable loss of diameter in the reinforcement

$$t_{secc,corr} = \Delta \varnothing_{lim} / \vartheta_{corr}$$

$\Delta \varnothing_{lim}$ is the variation in diameter due to corrosion of the reinforcement, which is considered inadmissible, expressed in μm

Carbonation example

Durability Annex 12 - Spanish Structural Code

Cross drainage work

Expossure class	XC2	Wet, rarely dry	
		Minimum	
c concrete cover mm	**20**	20	
f_{ck} N/mm^2	40	25	
f_{cm}	48		

Initiation corrosión carbonation for XC

$t_i = (c/K_c)^2$		64,23	years
$K_c = c_{env} \cdot c_{air} \cdot a \cdot f^{b}_{cm}$		2,496	
Tabla A.12.3.1.a	c_{env}	1	Protected from rain
Tabla A.12.3.1.b	c_{air}	1	Ocluded air < 4,5%
Tabla A.12.3.1.c	**a**	1800	Portland cement
	b	-1,7	

Propagation

Corrosion time to crack the cover

$t_p = 80 \cdot c / (Ø \cdot v_{corr})$	20,00	years
Ø maximun reinforcement diameter	20	mm
v_{corr} (tabla A.12.4.1)	4	μm/year

Corrosion time for an unacceptable loss of diameter

$t_{secc,corr} = \Delta Ø_{lim} / v_{corr}$	25,06	years
Admissible loss of steel area	1	%
$\Delta Ø_{lim}$ en μm	100	

Results

Initiation	64,23	years
Propagation	45,06	years
Expected service life	**109,29**	years

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Carbonation example

Durability Annex 12 - Spanish Structural Code

Cross drainage work

Expossure class	XC2	Wet, rarely dry	
			Minimum
c concrete cover mm	**25**		20
$\mathbf{f_{ck}}$ N/mm^2	40		25
f_{cm}	48		

Initiation corrosión carbonation for XC

	$t_i = (c/K_c)^2$	**100,36**	years
	$K_c = c_{env} \cdot c_{air} \cdot a \cdot f^b_{cm}$	2,496	

Tabla A.12.3.1.a	$\mathbf{c_{env}}$	1	Protected from rain
Tabla A.12.3.1.b	$\mathbf{c_{air}}$	1	Ocluded air < 4,5%
Tabla A.12.3.1.c	**a**	1800	Portland cement
	b	-1,7	

Propagation

Corrosion time to crack the cover

$t_p = 80 \cdot c / (\varnothing \cdot v_{corr})$	**25,00**	years
Ø maximun reinforcement diameter	20	mm
$\mathbf{v_{corr}}$ (tabla A.12.4.1)	4	µm/year

Corrosion time for an unacceptable loss of diameter

$t_{secc,corr} = \Delta \varnothing_{lim} / v_{corr}$	**25,06**	years
Admissible loss of steel area	1	%
$\Delta \varnothing_{lim}$ en µm	100	

Results

Initiation	100,36	years
Propagation	50,06	years
Expected service life	**150,42**	years

Chlorides ions penetration example

Durability Annex 12 - Spanish Structural Code

Submarine emisary

Expossure class	XS2	Permanently submerged		
	XA2	Moderately aggresive chemical environment		

		Minimum values 100 years	
		XS2	XA2
c concrete cover mm (Tables 44.2.1.1.a y b)	30	35	not defined
$\mathbf{f_{ck}}$ N/mm^2 (table 43.2.1.b)	50	30	30
Cement / $\mathbf{m^3}$ (table 43.2.1.a)	350	325	350
w/c ratio	0,45	0,5	0,5
t_0	0,0767		
C_s % s/cement	2,629		

Initiation income cloryde ions for XS or XD

Test time	**54**
$\mathbf{C_b}$ % s/cement	**0,2**
$\mathbf{C_s}$ % s/concrete (table A.12.3.2.a)	0,4
Cement /m³ (table 43.2.1.a)	350
n (table A.12.3.2.c)	0,5
Real temperature ºC	15
$\mathbf{D_{app,c}(t_0)}$ (table A.12.3.2.b)	6,9
Results	
K_e	0,752
$D_{app,c}(t)$	6,171
erf parenthesis	0,822
erf value	0,755
C_{th}	0,795
$\mathbf{C_{th}}$ limit (table A.12.3.2.1.a)	0,8	**valid**

Parabolic fórmula

A	0,50
B	1965
C	6,54
t	42,75
$\mathbf{C_{th}}$	0,871

Results

Initiation	54,00	years
Propagation	65,04	years
Expected service life	**119,04**	years

Propagation

Corrosion time to crack the cover

$t_p = 80 \cdot c / (Ø \cdot v_{corr})$	**50,00**	years
Ø maximun reinforcement diameter	12	mm
$\mathbf{v_{corr}}$ (table A.12.4.1)	4	µm/year

Corrosion time for an anacceptable loss of diameter

$t_{secc,corr} = \Delta Ø_{lim} / v_{corr}$	**15,04**	years
Admissible loss of steel area	1	%
$\Delta Ø_{lim}$ en µm	60	

Chlorides ions penetration example

Reducing the chlorides content from the materials from 0,2 to 0,1

Durability Annex 12 - Spanish Structural Code

Submarine emisary

Exposure class	XS2	Permanently submerged
	XA2	Moderately aggresive chemical environment

		Minimum values 100 years XS2	XA2
c concrete cover mm (Tables 44.2.1.1.a y b)	30	35	not defined
f_{ck} N/mm^2 (table 43.2.1.b)	50	30	30
Cement / m^3 (table 43.2.1.a)	350	325	350
w/c ratio	0,45	0,5	0,5
t_0	0,0767		
C_s % s/cement	2,629		

Initiation income cloryde ions for XS or XD

Test time	70
C_b % s/cement	0,1
C_s % s/concrete (table A.12.3.2.a)	0,4
Cement /m^3 (table 43.2.1.a)	350
n (table A.12.3.2.c)	0,5
Real temperature ºC	15
$D_{app,c}(t_0)$ (table A.12.3.2.b)	6,9
Results	
K_e	0,752
$D_{app,c}(t)$	5,420
erf parenthesis	0,770
erf value	0,724
C_{th}	0,798
C_{th} limit (table A.12.3.2.1.a)	0,8

valid

Parabolic fórmula

A	0,53
B	1965
C	7,37
t	54,26
C_{th}	0,880

Results

Initiation	70,00	years
Propagation	65,04	years
Expected service life	135,04	years

Propagation

Corrosion time to crack the cover

t_p=80 . c / (Ø . v_{corr})	50,00	years
Ø maximun reinforcement diameter	12	mm
v_{corr} (table A.12.4.1)	4	µm/year

Corrosion time for an anacceptable loss of diameter

$t_{secc,corr}$ = Δ $Ø_{lim}$ / v_{corr}	15,04	years
Admissible loss of steel area	1	%
Δ $Ø_{lim}$ en µm	60	

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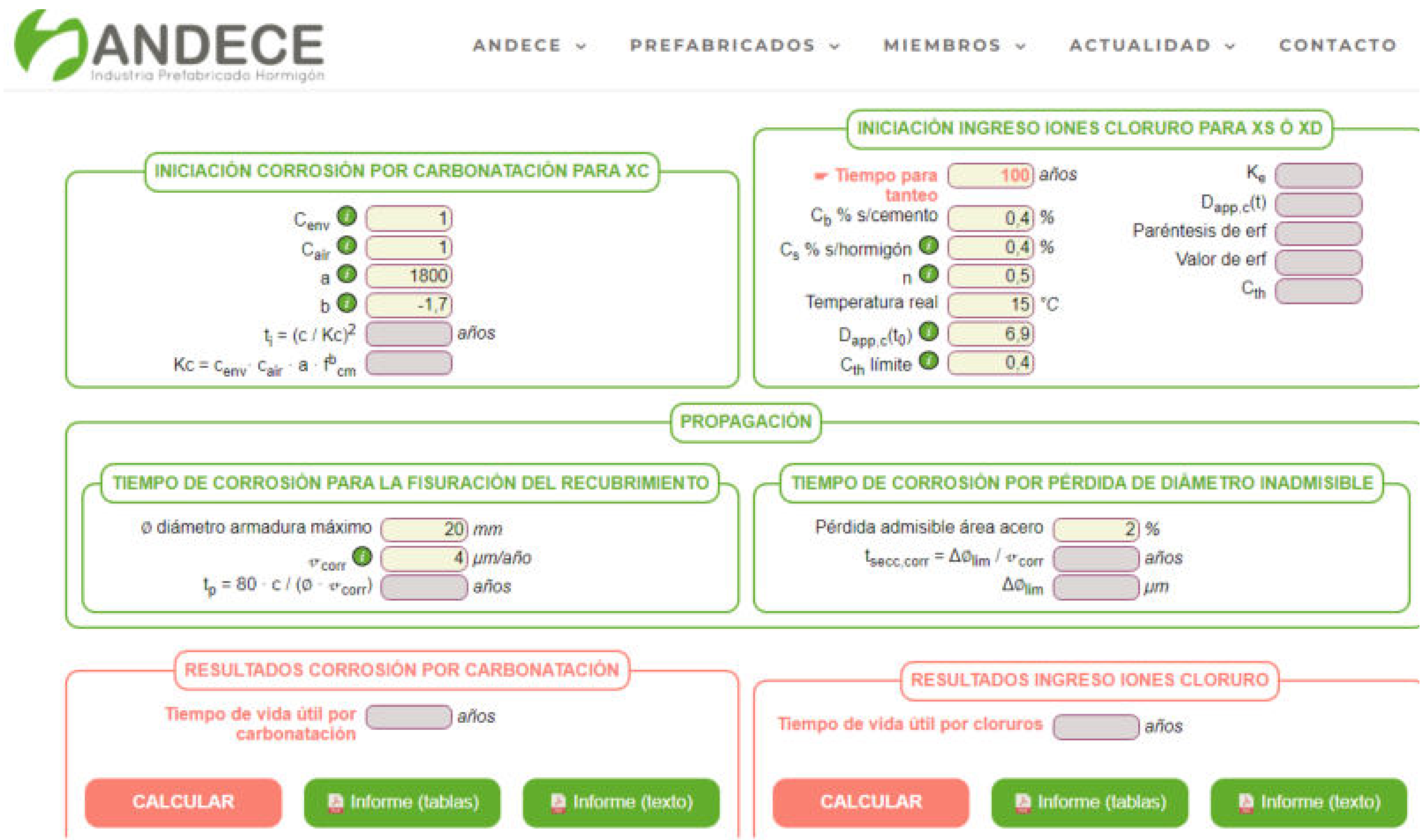
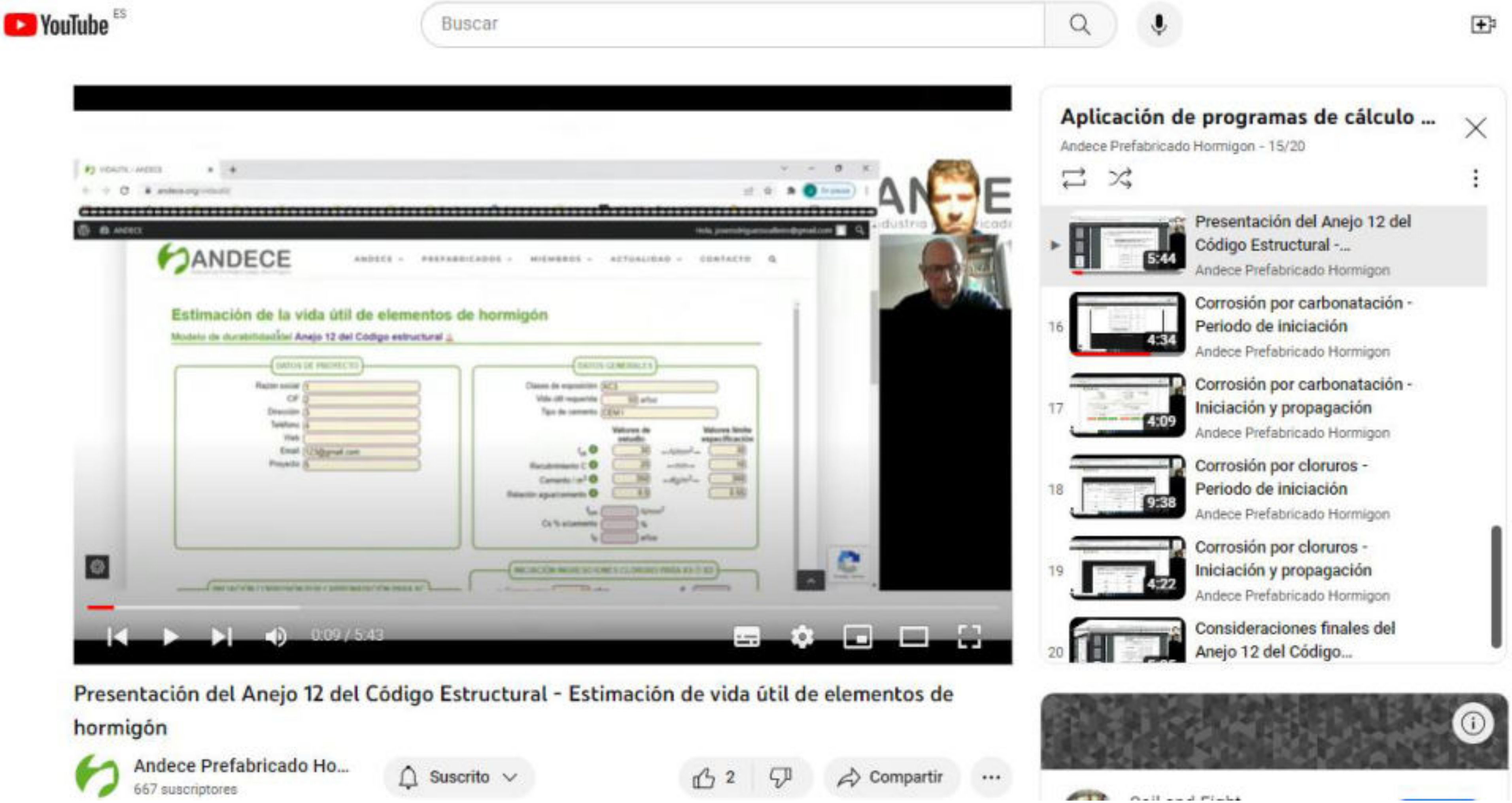
ANDECE SOFTWARE

- **Andece has developed a tool to facilitate the application of this annex to their members** [**www.andece.org**](http://www.andece.org)



CARBONATION EXAMPLE

MORE EXAMPLES



Videos at YouTube ANDECE channel: https://bit.ly/4669cbL

CONCLUSIONS (1)

➢ **Aspects to emphasize if we use this Annex:**

- **We can quantify the service life**
- **We can design elements with the service life we want to get**

Structural performance

Structural durability

CONCLUSIONS (2)

- If we improve the minimum requirements of the standards, it allows us to reduce the concrete cover
- Let solve cases of structures in very aggressive environments where the code provisions does not provide a fully defined durability strategy
- If we design elements with a longer service life, we can amortize the environmental impacts by dividing them into a much longer period

	Case 1	Case 2
GWP Global Warming Potential (all the life cycle)	Environmental footprint 150 kg CO_2eq/Tn	
Service life (years)	50	↑ 150
GWP/year (kg CO_2eq/Tn/year)	3	↓ 1

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METHODOLOGY TO EVALUATE THE SERVICE LIFE OF CONCRETE

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Many thanks for your attention…

Any question?